

# A SEQUENCE OF DECLINING OUTBURSTS FROM GX339-4

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## ABSTRACT

The flux and spectrum of the black hole candidate GX339-4 has been monitored by the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-ray Observatory (CGRO) since the observatory became operational in May 1991. Between the summer of 1991 and the fall of 1996, eight outbursts from GX339-4 were observed. The history of these outbursts is one of declining fluence or total energy release, as well as a shortening of the time between outbursts. A rough linear correlation exists between the fluence emitted during an outburst and the time elapsed between the end of the previous outburst and the beginning of the current one. The peak flux is also roughly linearly correlated with outburst fluence. The lightcurves of the earlier, more intense, outbursts (except for the second one) can be modeled by a fast exponential (time constant  $\sim 10$  days) followed by a slower exponential ( $\sim 100$  days) on the rise and a fast exponential decay ( $\sim 5$  days) on the fall. The later, weaker, outbursts are modeled with a single rising time constant ( $\sim 20$  days) and a longer decay on the fall ( $\sim 50$  days). An exponential model gives a marginally better fit than a power law to the rise/decay profiles. GX339-4 is a unique source in having more frequent outbursts than other low mass x-ray binary black hole candidates. These observations can be used to constrain models of the behavior of the accretion disk surrounding the compact object.

*Subject headings:* binaries:general — black hole physics — stars:individual(GX339-4) — X-rays:stars

## 1. INTRODUCTION

Much effort has been made to study the x-ray source GX339-4 since its original discovery by OSO-7 (Markert, et al. 1973). GX339-4 is usually considered a black hole candidate (BHC) due to the similarity of its x-ray spectral and timing states to dynamical BHC such as Cygnus X-1, and to the lack of detection of pulsations or x-ray bursts. However, there is considerable uncertainty about the mass of the compact object, and GX339-4 is not at this time a dynamical BHC (Callanan, et al. 1992). However, it is similar to the two established jet sources GRS1915+105 and GROJ1655-40, the latter a dynamical BHC, in exhibiting multiple hard x-ray outbursts. The recent report of a weak radio jet in GX339-4 (Fender, et al. 1997) (the velocity of the jet is essentially unknown) is a hint that these three sources may be fundamentally similar (Zhang, et al. 1997). The existence of the radio jet requires confirmation from future observations.

Most x-ray observations of GX339-4 have focused on determining which of four x-ray spectral states (off, low, high, very high) the source is in, and describing the properties of those states (Motch, et al. 1985, for a recent review see Tanaka and Lewin 1995). Here we will present new data from six recent outbursts observed by CGRO-BATSE. Our analysis will also include two earlier outbursts observed by BATSE (Harmon et al. 1994). The eight outbursts observed by BATSE can be roughly divided into two types based on the outburst fluence, light curve, spectral evolution, and recurrence pattern. In these respects, the first four outbursts appear to be different from the last four.

More important than this classification, however, is the observation that the general pattern of these outbursts is one of decreasing total energy release, as subsequent outbursts occur closer together in time, so that outburst fluence in the 20-300 keV band is correlated with the time elapsed since the previous outburst.

## 2. OBSERVATIONS

Figure 1 shows the BATSE flux history obtained using the Earth occultation technique and an optically thin thermal bremsstrahlung (OTTB) spectral model fit to the observed count rates in the 20-300 keV band. The functional form of the OTTB model used is  $A \exp(-E/kT)/E$  where  $E$  is the photon energy in keV and the amplitude  $A$  and temperature  $kT$  (in keV) are determined from the fit. The observational techniques are described in (Harmon et al. 1994).

Figure 1 shows eight outbursts separated by intervals during which the source was not detected above the  $\sim 30$  mCrab threshold for ten day integrations. We will label these outbursts B1-B8. The first three outbursts have similar lightcurves and recur at an approximately periodic interval of  $\sim 450$  days. However, neither the profiles nor recurrence intervals of the later outbursts, especially the last four, show evidence of being related to the earlier outbursts. Information on outburst beginning and ending times, peak fluxes and times, and total fluences appears in Table 1.

Three spectral models: OTTB, photon power law (PL), and Sunyaev-Titarchuk comptonization (ST) (Sunyaev & Titarchuk 1980) were fit to the data over 20-300 keV. An OSSE observation near the peak of B1 was consistent with an OTTB model ( $kT \simeq 70$  keV) over the full energy range in which the source was detected (up to 400 keV), but inconsistent with PL and a marginal fit at best to ST above 200 keV (Grabelsky et al. 1995). During almost all of B1-B4, PL gives unacceptable fits to the BATSE data, while the OTTB and ST models are both adequate, and fit equally well. Table 2 shows a comparison of PL and OTTB model fits during selected intervals. While an OTTB model also always works during B5-B8, there are also times during these outbursts when PL gives equally good fits. During these times, the possibility that the spectrum is a power law which also extends to higher energies can not be ruled out, though it is also possible that an OTTB

spectrum is always correct.

The spectral evolution during each outburst is presented in a plot of OTTB fit temperature versus time in Figure 2. During outbursts B1-B4 the temperature peaked early and declined gradually. In contrast, it remains roughly constant during B5-B8.

### 3. ANALYSIS OF THE OUTBURST PATTERN

We have used the information in Table 1 to examine the possibility of correlations among the outburst fluence, peak flux, duration, and time between outbursts.

The left panel of Figure 3 shows that peak flux is roughly linearly correlated with the total outburst fluence, over a factor of 3.5 in each parameter, as first reported in Robinson et al. 1996. Peak outburst luminosities depend on source distance, which has been estimated between 1.3 kpc (Predehl et al. 1991) and 4 kpc (Cowley et al. 1987). The peak luminosities range from  $2.2 \times 10^{35} d_{kpc}^2$  ergs/s for B5 to  $7.6 \times 10^{35} d_{kpc}^2$  ergs/s for B3 where  $d_{kpc}$  is the source distance in kpc.

In the right panel of Figure 3 the time elapsed since the previous outburst ( $T_{pi}$ , the time between the end of the previous burst B(i-1) and the start time of Bi) is plotted versus outburst fluence. An approximate linear correlation between  $T_{pi}$  and fluence is observed, with the possible exception of B5, which appears underluminous for this relation. If we consider instead the time until the next outburst, the deviations of B1 and B3 from the trend are quite large. Thus, taking the time since the previous outburst as the underlying variable correlated with outburst energy release is the better description of source behavior. This correlation implies that the time averaged luminosity,  $\bar{L} = 1.6 \times 10^{35} d_{kpc}^2$  ergs/s, is roughly constant. Outburst durations show no clear trend when plotted against fluence.

#### 4. OUTBURST TIMESCALES

Spectral fits in which flux is the only free parameter were used to obtain a flux estimate for each day of data. In each fit, the temperature is held fixed at the temperature determined from the corresponding ten day spectral fit. We have attempted to model the first four outbursts (except for the second one) with an initial fast exponential rise followed by a second, much slower, rise. The last four outbursts (and the second one) have only a single rise, and each outburst has a single decay.

Figure 4 shows the one day resolution lightcurves of B1 and B5. Information about rise and decay times of all of the outbursts is given in Table 3. In each case the rise (including variable break time) and decay intervals were fit separately.

For comparison we have also fit power law models to each rise/decay portion of the lightcurve. F-test probabilities that the power law model is preferred range from 3% to 85% and are typically about 30%. Only on the fall of B1 and the rise of B3 is this probability above 50%. Exponential models are thus marginally preferred.

#### 5. DISCUSSION

In the past GX339-4 has been mostly observed sporadically by pointed instruments, making it difficult to discern any long term outburst pattern. Our analysis suggests that during the observations presented here, there is a pattern in hard x-rays consisting of a sequence containing two types of outburst with declining fluence in the 20-300 keV band.

Nearly continuous observations made with the Ginga All Sky Monitor (ASM) in the 1-20 keV band between early 1987 and the fall of 1991 indicate that this hard x-ray pattern may also be followed in soft x-rays (Kitamoto, S. 1992). During this time Ginga observed three outbursts, which also follow a pattern of declining fluence, and which could be an

earlier part of the sequence observed by BATSE. The first and brightest outburst occurred after a long quiet period ( $> 1.5$  years). During this outburst, the very high state was observed, probably the only time it has been observed in this source. The third outburst, which occurred near the end of the operational life of Ginga and was only partially observed, was coincident with B1. A hard to soft transition occurred about  $\sim 50$  days into this outburst, but there was otherwise no unusual soft x-ray activity. These observations suggest the possibility that the first outburst observed by Ginga initiated the subsequent declining sequence. However determining, whether, and to what extent, the patterns observed here in the BATSE data are also relevant below 20 keV, and in particular, the effect of x-ray spectral state changes, will require more careful analysis of existing multi-instrument data.

For a constant mass accretion rate from the companion into an accretion disk, the correlation between fluence and recurrence time found here implies that just the excess mass which accumulates in the disk between outbursts falls into the compact object during the outbursts. The rise and decay profiles of the outbursts are related to how the matter passes through the disks, and therefore to the properties of nonstationary accretion disks. For example, exponential timescales in nonstationary disks have been shown to imply a linear relation between the diffusion coefficient and surface density; a non-linear relation would imply power law profiles (Liubarskii and Shakura 1987).

A thermal instability in an outer thin disk can account for the recurrence, rise, and decay times of soft x-ray transients (SXT) (Mineshige 1996). The outburst recurrence time is identified with the viscous timescale in the "cool" (low  $\alpha$ ) branch of the outer disk and the decay timescale with the "hot" branch ( $\alpha$  is the dimensionless viscosity). Thus,  $t_{vis} = (R/H)^2(\alpha\Omega)^{-1} \simeq 10\sqrt{mR_1}(\alpha T)^{-1}$  where  $m$  is the compact object mass in solar masses,  $R_1$  the disk radius in  $10^{10}$  cm and  $T$  the temperature in  $10^4$  K. "Cold"  $\alpha \sim 0.001 - 0.01$  implies a recurrence time of one to several years and "hot"  $\alpha \sim 0.1 - 1.0$  a

decay time of 10-100 days. The rise time is the sound speed propagation time in the outer disk:  $t_{rise} = R(\alpha C_s)^{-1} \simeq 0.1 R_1 (\alpha T)^{-1/2}$ , on the order of a day for  $\alpha \sim 0.1$ .

Can similar arguments be applied to the case of GX339-4? Perhaps only the fast decay times can not be explained in this way. These might instead imply a shrinking of the thin disk radius,  $R_1$ , by a factor of at least 10 or more during the outburst. Shrinking may also suggest an explanation for the dual risetimes in the early outbursts. If these outbursts originate deep inside the thin disk, then the fast risetime represents the propagation of the heating front throughout the disk, while the slow risetime is the viscous timescale on which the hot outer disk shrinks, as it pushes matter into the inner disk. In this scenario, the first four outbursts are "inside-out" with a shrinking disk while the last four, with behavior closer to SXT, may be "outside-in". Time differences between the origin of optical and x-ray radiation at the beginning of an outburst can discriminate the direction of the outburst. For example, an outburst of GROJ1655-40 was seen to be outside-in (Orosz et al 1997). Such observations are strongly encouraged.

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Fig. 1.— BATSE lightcurve. Photon flux as a function of time in the 20-300 keV energy band as determined from an optically thin thermal bremsstrahlung fit to Earth occultation data. Horizontal bars indicate the data integration interval. The vertical error bars are statistical only. Additional systematic uncertainties can arise from faint sources causing interference along occultation edges. The data is histogrammed when an outburst is in progress. The numbers near the bottom of the plot label each of the outbursts B1-B8 (the B is omitted on the plot). The dotted line is at the level of zero flux.

Fig. 2.— Spectral Evolution of the outbursts. The spectral evolution of each outburst is shown as a plot of OTTB model temperature in the 20-300 keV band as a function of time since the beginning of the outburst. The plot symbol corresponding to each outburst is shown in the insets. Horizontal bars indicate data integration intervals. The vertical error bars are statistical only. The starting times of the outbursts are listed in Table 1 under the column heading 'Beginning Time'.

Fig. 3.— Outburst parameters vs. outburst fluence in the 20-300 keV band. In each of these plots, the number near each data point labels the corresponding outburst (B1-B8). See Tables 1 and 3 for the values used in the plots. Left panel: Outburst fluence versus peak flux. Error bars are statistical only. The dotted line shows the best fit straight line to the plotted data. Right panel: Outburst fluence versus time to the previous outburst  $T_{pi}$ . Vertical error bars are statistical only and horizontal bars show an approximate uncertainty of 10 days in  $T_{pi}$ . The dashed line is the best fit straight line.

Fig. 4.— One day resolution outburst lightcurves and model fits. Top: B1. Time zero on the horizontal scale corresponds to Julian day 2448430. Bottom: B5. Time zero corresponds to JD 2449840. Vertical error bars are statistical only and horizontal bars show the data integration interval. The solid lines show the exponential rise and decay models discussed in the text. The rise and decay timescales obtained from the fits are listed in Table 3.

Outburst	Beginning Time JD-2440000	Ending Time JD-2440000	Peak Time JD-2440000	Peak Flux photons/cm <sup>2</sup> s	Fluence ergs/cm <sup>2</sup>
B1	8437	8537	8505	$0.107 \pm 0.002$	0.038
B2	8887	8982	8958	$0.086 \pm 0.002$	0.048
B3	9345	9438	9398	$0.106 \pm 0.001$	0.054
B4	9620	9691	9658	$0.077 \pm 0.001$	0.032
B5	9851	9937	9865	$0.040 \pm 0.001$	0.014
B6	9956	10025	9956	$0.036 \pm 0.002$	0.016
B7	10107	10168	10126	$0.043 \pm 0.001$	0.016
B8	10268	10347	10288	$0.043 \pm 0.001$	0.023

Table 1: Outburst Beginning, Ending, and Peak Times, Fluxes, and Total Fluences. Peak fluxes in each outburst are calculated as the largest average of three consecutive time integrations. Peak times are at the center of these averages.

Outburst	Times	OTTB Temperature	$\chi^2_{OTTB}$	PL index	$\chi^2_{PL}$	$\nu$
B1 (R2)	8504-8511	$61 \pm 3$	20	2.4	94	16
B2 (M)	8950-8957	$78 \pm 5$	33	2.2	65	25
B3 (R2)	9368-9384	$70 \pm 3$	51	2.2	108	34
B4 (R2)	9643-9657	$65 \pm 3$	59	2.2	79	34
B5 (M)	9874-9898	$86 \pm 7$	93	2.1	93	70
B6 (R)	9951-9967	$77 \pm 9$	16	2.2	22	16
B7 (M)	10126-10147	$87 \pm 6$	45	2.0	79	46
B8 (D)	10308-10322	$96 \pm 22$	41	2.0	47	32

Table 2: OTTB and Power Law (PL) Spectral Fits in the 20-300 keV range. The portion of the outburst from which the data is drawn is given in parentheses in the Outburst column. R = Rise; R2 = Second rise; M = Middle; D = Decay. The times are in JD-2440000.5 (Truncated Julian Days). Uncertainties in the power law index are 0.1 or less.  $\nu$  is the number of degrees of freedom in each of the spectral fits. Nine channels from each detector in each spacecraft pointing interval were used. Most of the fits encompass multiple pointing intervals.

Outburst	Previous	Duration	Rise 1	Rise 2	$\chi^2_{\nu rise}(\nu)$	Decay	$\chi^2_{\nu decay}(\nu)$
B1	-	100	$12.7 \pm 1.5$	$153 \pm 52$	1.6 (65)	$5.7 \pm 0.5$	1.5 (5)
B2	350	95	-	$108 \pm 25$	0.9 (39)	$3.4 \pm 0.5$	0.8 (8)
B3	363	93	$7.6 \pm 1.5$	$104 \pm 12$	3.8 (73)	$8.9 \pm 0.9$	0.6 (10)
B4	182	71	$21 \pm 11$	$56 \pm 12$	1.4 (37)	$5.8 \pm 0.8$	0.5 (6)
B5	160	86	$19 \pm 13$	-	0.8 (8)	$56 \pm 14$	1.0 (36)
B6	19	69	$18 \pm 7$	-	1.0 (8)	$55 \pm 24$	1.3 (22)
B7	82	61	$13.5 \pm 2.6$	-	0.7 (16)	$12.6 \pm 3.6$	0.8 (11)
B8	99	79	$47 \pm 6$	-	1.3 (32)	$64 \pm 18$	0.7 (13)

Table 3: Timescales During Outburst Sequence. The second column (labeled Previous) is  $T_{pi}$ , the time between the end of the previous and the beginning of the current outburst. Duration is the duration of the outburst, given by the difference between the beginning and ending times in Table 1. Rise 1 is the first e-folding rise time and Rise 2 the second e-folding rise time determined from an exponential model fit (with variable break time, when both timescales are present) on the rising portion of the outburst. Decay is the e-folding decay time from an exponential model fit on the falling side of the outburst. All times are in days. The reduced  $\chi^2$  and corresponding number of degrees of freedom,  $\nu$ , are shown for each fit.









